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Integration of environmental aspects into R&D inter-organizational projects management: application of a life cycle-based method to the development of innovative windows

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ABSTRACT

Within Research and Development programmes funded by the European Union, new generations of materials, products, systems, and processes are under development. In the present article the structure of a Research and Development publicly funded inter-organizational project with its deliverables and milestones is analysed, since it can enhance the development of real eco-innovation. In particular the technical and managerial experience gained during EU-funded FP7 project called HarWin (Harvesting solar energy with multifunctional glass-polymer windows) is reported. The project aimed at designing innovative smart windows with polymer-glass composite glazing and framing. As Life Cycle Assessment has been increasingly explicitly required in R&D projects, efforts have been dedicated to enlarge knowledge on the development of specific tailored LCA methods and tools and on the application of LCA in inter-organizational R&D projects in general. The specific method developed and systematically tested within the project to assess the environmental burden associated to the life cycle of windows at the R&D stage is reported. The specific tool that has been developed to allow environmental data gathering and direct involvement of the design team in the environmentally conscious design of the window is also described, highlighting its experienced benefits. The management of the HarWin project has been analysed and reported in order to identify strengths and weaknesses for the integration of environmental aspects and of LCA in particular. Finally, a list of recommendations for improving the planning in future calls and the execution of future projects is reported.

1. Introduction

The implementation during the product development process of environmental strategies is fostered by various drivers, including customers' requirements, policies (e.g. product policies such as Ecodesign Directive (Directive 2009/125/EC) or EU Ecolabel (Regulation (EC) N. 66/2010), waste policies such as Waste framework Directive (Directive 2008/98/EC) or Waste Electric and Electronic Equipment Directive (Directive 2012/19/EU), chemical related policies such as RoHS Directive (Directive 2011/65/EU) and REACH regulation (Regulation (EC) N.1907/2006)) and standardization activity. The environmental part of product stewardship, Eco-design, Design For Environment (DFE) are all terms used as synonyms by ISO/TR 14062 (ISO/TR 14062, 2002) for the "integration of environmental aspects into product design and development", given that "product development" is "the process of taking a product idea from planning to market launch and review of the product, in which business strategies, marketing considerations, research methods and design aspects are used to take a product to a point of practical use". Environmentally conscious R&D is now also encouraged by Publicly Funded Research Programmes. The European Union's Research and Innovation funding programme for 2007–2013 (FP7) and Horizon 2020 calls, explicitly require bringing environmental aspects within the innovative products development and Life Cycle Assessment (LCA) as a mean to do it. As the importance of the life cycle approach in industrial product

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development and in many field of materials, products and systems innovation was well recognized and documented, the concept of environmentally conscious R&D taking a life cycle approach have been introduced by the EU's main instrument for funding research in Europe. In 2007 the Life Cycle perspective has been formally introduced within the FP7 calls. In particular the Decision N° 1982/2006/EC (Decision, 2006) includes these objectives:

- “The development and validation of new industrial models and strategies covering all aspects of product and process life-cycle”;
- “Control of intrinsic properties and performance, processing and production taking into account potential impacts on health and the environment throughout their entire life cycle.”

Consequently, the life cycle approach has been explicitly introduced in some calls of the FP7 in 2009–2010. In particular “the Nanotechnology, Materials & Production (NMP) Theme in the FP7 Cooperation scheme has taken stock of this, by for example including aspects such as substitution, life cycle assessment, improved resource efficiency and better performance materials in the NMP calls for proposals” (Benesch and Tomellini, 2013). Many NMP calls (European Commission, C(2011)5068) (e.g. Innovative materials for advanced applications calls or Public-Private Partnerships calls such as Green Cars, Factories of the Future, Energy-efficient Buildings) explicitly require eco-design and appropriate life-cycle analysis to assess health and environmental impacts of each developed solution. In some specific calls (e.g. for Halogen-free flame retardant materials (NMP.2012.2.2-5) or in the building sector and in particular for “Smart Windows” (EeB.NMP.2012.5)), LCA is proposed as a tool to support decisions and the International Reference Life Cycle Data System (ILCD) handbook (EC-JRC-IES, 2010) and ISO 14040 family (ISO:14040, 2006; ISO:14044, 2006) are required to be used as guidance. This approach is expected to be continued in future calls, also considering that in the Horizon 2020 – Work Programme 2014–2015 “Nanotechnologies, Advanced Materials and Production” (European Commission Decision C(2014) 4995), the life cycle perspective to assess the environmental performances of the solutions is explicitly required in several calls. Moreover in some calls for proposal, projects are required to further address the complexity of sustainability, including the assessment of social, environmental and economic implications of the whole supply chain of products. In this regards life cycle sustainability assessment (LCSA) represents a promising approach. It has been developed (Guinée et al., 2011; Kloepffer, 2008) as a combination of environmental life cycle (LCA), life cycle costing (LCC) and social LCA (sLCA) and has been already tested for same technological applications (Traverso et al., 2012) even if further improvement are necessary for its methodological and scientific development (Sala et al., 2013). Nevertheless, what is explicitly required in research calls for proposals still finds some obstacles in the practical application. A survey (Benesch, 2012) towards NMP projects' co-ordinators was led by DG Research and Innovation to analyse the degree of success of the funding policy and to understand better how project consortia view environmental issues: 74% of 61 respondents (out of 103 NMP projects questioned) claim to consider environmental aspects in their projects; 44% did not include any formal procedure to handle environmental issues because they considered their project as “too theoretical or basic science”; only 28% of respondents declared to use LCA according to ILCD or ISO 14040.

From the results of the survey it emerges that it is worth analysing which reasons constitute the main obstacles for the systematic integration of environmental aspects in inter-organizational publicly funded R&D Projects. Maybe because of its novelty, the topic of the use of LCA in R&D Projects is still poorly addressed by academics: we only found one very recent scientific paper dealing with these issues in the literature (Sandin et al., 2014).

Conversely the integration of environmental aspects in product development projects within enterprises is well documented (see e.g. Froelich et al., 2007; Le Pochat et al., 2007; Millet et al., 2007; Brones et al., 2014). Through the analysis of successful experiences and issues faced by companies, the following relevant obstacles to the implementation of LCA in the Product Development process (PDP) have been identified:

- Lack on integration of environmental dimension into the project management (Brones et al., 2014; Dufrene et al., 2013): despite the availability of methods and tools for evaluating environmental aspects (Bovea and Perez-Belis, 2012), industrial utilization is still limited (Lindahl, 2006), in particular due to project management guidelines that do not systematically consider environmental aspects (Dufrene et al., 2013);
- Cost issues: integration of environmental aspects are often perceived by companies are too costly (Baumann et al., 2002);
- Timing issues: a tool like LCA, as a support to environmentally conscious design, can be time consuming while deadlines in projects are usually very tight (Brones et al., 2014); delay on the integration of environmental aspects in PDP bring to the decrease of the possibility to influence the design choices (Bovea and Perez-Belis, 2012);
- Insufficient knowledge of the environmental issues by the product developers: Baumann et al. (2002) point out that: “Environmentally conscious design and manufacturing (ECDM) presents one of the most difficult challenges engineers have ever faced. It requires them to consider issues outside their area of expertise, far beyond the boundaries of the individual firm”. It comes out the need to define the approaches for the integration of the environmental dimension in the Design team (D-team hereafter);
- Lack of follow-up on the choice of methods and tools: it implies the risk that the person in charge of taking formal decisions receives the wrong indications from the users (engineers/designers) about how the method or tool fulfils his or her intentions and goals (Lindahl, 2006); Millet et al. (2007) raise concern on the reliability of the outputs, and on the lack of understanding of the impact category by the D-team;
- Perception of LCA as a stumbling block to creativity: according to Millet et al. (2007), a tool like LCA can represent an obstacle to the freedom of the creativity that is required for the development of new products;
- Uncertainty on how to prioritize environmental issues against other factors (Bovea and Perez-Belis, 2012): this step is often seen as a highly subjective activity (Millet et al., 2007). “It is easy to understand how technical, energy, environmental and economic matters, taking part at the same time in the design process, make hard the choice of decisions” (Ardente et al., 2003);
- Difficulties in collecting reliable and detailed data: a huge amount and variety of high qualitative data are necessary, especially when conducting an LCA (Dufrene et al., 2013; Lindahl, 2006).

On the other hand, there have been also a lot of reported successful experiences on the integration of LCA in PDP. According to Le Pochat et al. (2007), the most common way to initiate an eco-design project is through a partnership between a research centre and a company. In that way, experts in environmental analysis from the research centre bring the necessary expertise related to LCA methods and tools, overlapping one of the main issues that consists in how to transfer to the members of a company the knowledge to carry out internally the environmental analyses.

Froelich et al. (2007) report a successful example of the integration of a design-for-recycling tool in the design process of an automotive manufacturer. It has been developed within a research project commissioned by the company itself to implement recycling concepts since the early stage of development of a new generation of vehicles. In this case there is a further integration of environmental concerns in the company management: at the beginning, the experts of the research centre collected information on sorting process availability and material compatibility and made specification sheets for car components, but later, the members of the company itself translated and simplified those information into a tailored tool to be used by the D-teams of the company. This paper witnesses the willingness to adapt the tools and the environmental knowledge into the decision process of the organization.

Ardente et al. (2003) also describe a successful experience of a model implemented in a software to support the decision-maker in an environmentally-conscious design in the field of electricity distribution facing the problem that arises in the multiple criteria decisional processes where there are a lot of information of a complex and conflict nature, that reflect different and changeable points of view.

Coming back to inter-organizational consortia and in particular from the analysis of successful implementation in NMP projects reported in the above mentioned survey (Benesch, 2012), it emerges that the future success of the integration of environmental aspects depends upon various aspects, including the type of calls, the project itself, the partners, the access to source of data (including confidential data) and knowledge or the methodology and tools to be used. Like companies, inter-organizational consortia working on R&D encounter obstacles in the implementation of environmentally conscious design on the PDP. According to Sandin et al. (2014), some specific issues related to this kind of consortia are listed below:

- Inter-organizational research projects are characterized by cultural complexity since members from academia, firms and research institutes work together. This brings new synergies, important for improving creativity (key issue in R&D projects), but also different expectations on the project outcomes (Sandin et al., 2014).
- The main object of R&D projects is to develop new material/system/manufacturing processes. Because of the novelty of these products/processes, the reliability of Life Cycle Inventory (LCI) data (Sandin et al., 2014) could be affected by the low quality or lack of environmental information.

To conclude Sandin et al. (2014) recommend enlarging the few reported experiences on LCA to support R&D inter-organizational projects to evaluate the possible roles of LCA and how they affect the project plans.

This paper aims to implement this recommendation by reporting the experience gained by several partners of a consortium that were striving at better take into account environmental aspects in the course of the EU-funded project HarWin (August 2012–August 2015). After this introductive section, Section 2 presents the analysed case study, the innovative smart window developed during the Project. Section 3 describes the life cycle assessment (LCA) method and tool that have been tailored on the window's specific features whereas Section 4 describes their application during the R&D process to develop an environmentally conscious R&D solution. Section 5 summarizes the obstacles and the opportunities found in the application of LCA for the development of a novel product within the frame of an inter-organizational R&D project. Section 6 presents concluding remarks.

2. Description of the case study

2.1. Environmental relevance of windows

The case study used in this paper is the implementation of environmental considerations in the design of innovative windows developed within one of the five R&D projects funded under the FP7 on “Smart Windows” (EeB.NMP.2012-5).

Together with the implementation of renewable energies, energy savings are crucial toward realizing sustainable development (Hee et al., 2015). The Life Cycle approach has been recently adopt to evaluate environmental drawbacks of both the renewable energy technologies (Asdrubali et al., 2015) (e.g. solar thermal (Burkhardt et al., 2011), solar photovoltaic (Fthenakis and Kim, 2011) and geothermal (Bayer et al., 2013)) and the energy-related technologies which contribute to the energy savings (Cellura et al., 2014) (e.g. insulation materials (Ardente et al., 2008) and bathroom devices, i.e. biomass boilers, shower heads, taps (JRC-EC, 2011)). Since 40% of energy consumption in EU is estimated to be related to the construction sector (Eurostat, 2010) to foster sustainability in the construction sector is a promising strategy. Windows directly affect the energy consumption and the environmental impacts during the use stage of buildings as they are typically responsible for a large fraction of the heat loss in buildings (Appelfeld et al., 2010) (up to 60% according to Gustavsen et al. (2007)) and as the energy consumption related to these losses (in the EU-27) amounts to 600–700 TWh in 2012 (http://www.ecodesign-wind). Moreover, windows deeply affect the energy consumption associated to lighting (Selkowitz and Johnson, 1980). Windows are also responsible for relevant environmental impacts due to the manufacturing and end of life phases. For example, according to Tarantini et al. (2011), the environmental impact of production process varies from 10 to 60% of the life cycle impacts of the window. It has been estimated (based on (http://www.ecodesign-windows.eu)) that almost 9 million tons of CO_2-eq were emitted in EU-27 for the production of the new windows put in the market in 2012. Therefore it comes out the importance of adopting a holistic approach which assesses all the phases on window's life.

The application of LCA methods and tools can be used to compare building components alternatives and lead building professionals towards using more sustainable and environmentally-friendly substitutes. From a recent review on existing studies by Salazar and Sowlati (2008a), it emerges that there is a significant amount of literature on LCA applications to windows. LCA studies are carried out on windows for three main reasons:

- To address the “cradle to gate” environmental impacts of a window or of a new under development technology for the frame (Basbagill et al., 2012) or the glazing system (Syrrakou et al., 2005; Papaefthimiou et al., 2001);
- To understand from a comparative “cradle to gate” assessment which frame material (e.g. wood, aluminium, wood-metal, PVC, steel, glass fibre reinforced polyester) (Asif et al., 2002, 2005; Recio et al., 2005; Menzies, 2013; Sinha and Kutnar, 2012; Stichnothe and Azapagic, 2013) or glazing system (Syrrakou et al., 2005; Syrrakou et al., 2006; Babaizadeh and Hassan, 2013) has a lower environmental impact;
- To address the “cradle to grave” environmental impacts of a window to avoid the shifting of the environmental impact from one phase of the life cycle to another, in particular to analyse how energy optimizations, carried out during the use phase, affect the environmental impact during manufacturing and

End-Of-Life (Tarantini et al., 2011; Baldinelli et al., 2014; Papaefthimiou et al., 2009; Minne et al., 2015; Babaizadeh et al., 2015; Salazar and Sowlati, 2008b; Citherlet et al., 2000).

Finally there are also studies which address at building level the effect of optimization of windows parameters (e.g. Window to wall ratio (Asdrubali et al., 2013) or thermal efficiency (Ardente et al., 2011) with the ultimate objective of avoiding environmental drawbacks over the building life cycle while reducing energy consumptions (Fesanghary et al., 2012).

The last approach aims at the integration of the product level assessment (window) into the system level assessment (building), and it is in line with the on-going activity carried out at the regulatory level by CEN TC350 (http://portailgroupe.afnor.fr), which is responsible for the development of a standardized and harmonised European method for buildings and building products environmental assessment. Among other things, the present article aims at showing how this increasingly adopted approach has been brought into the R&D design process carried out by an inter-organizational consortium. Recently, windows have been also of high interest within the European policy activity. The product group "Windows" has been regulated by the Construction Products Regulation (Regulation (EU) N. 305/2011) and indirectly by the Energy Performance of Buildings Directive (Directive 2002/91/EC). The Working Plan for energy-related products (2012–2014) in the context of the Ecodesign Directive (Directive 2009/125/EC), adopted by the Commission (SWD (2012) 434 final), includes windows among the priority product groups for an energy labelling scheme. The Working Plan estimates the energy savings potential to be reached through Ecodesign requirements in 785 PJ/year as of 2030. In this context the "Preparatory study on the Ecodesign of Window Products" (http://www.ecodesign-windows.eu) has been carried out (July 2013–May 2015) with the aim of evaluating potential measures on Ecodesign and Energy Labelling of windows.

Finally, windows and fenestrations are amongst the components of the building envelope those that are developing faster in the last years in terms of new materials and new processes development (Jelle et al., 2012). Materials with new properties are key to the future competitiveness of European industry and the basis for technical progress in many areas (Decision N. 1982/2006/EC). This is also an important reason for evaluating the life cycle environmental loads of windows while they are still at the design stage, since once new products are put on the market it is too late to raise environmental concerns (European Commission, COM(2001) 68; Ardente and Mathieux, 2014).

Based on these considerations, an inter-organizational R&D project aiming at developing innovative windows is considered as a relevant case study to analyse the integration of life cycle aspects in this kind of projects.

2.2. Specific FP7 call for proposal on 'Smart Windows'

There have been several EU funded calls within the FP7 specifically addressed for the development of "Smart Windows". The HarWin project has been funded within the 2012 Cooperation Specific Programme. This Specific Programme of the FP7 adopted a cross-thematic research areas approach: a joint call in the context of the Public-Private-Partnership (PPP), "Energy Efficient Buildings Initiative" (FP7, 2012), was launched involving five themes: Information and Communication Technologies (ICT); Nanosciences, Nanotechnologies, Materials and new Production Technologies (NMP); Energy; Environment (including climate change). The specific topic of "smart windows" has been financially supported by the theme NMP: the EeB.NMP.2012-5 is the specific call for proposals on "Novel materials for smart windows conceived as affordable multifunctional systems offering enhanced energy control".

In particular the "Smart Window" call asked that "the proposed solutions should go well beyond the state of the art, e.g. in terms of embodied energy and durability, respect of sustainability principles" and that the "environmental sustainability of each developed solution should be evaluated via life cycle assessment studies carried out according to the International Reference Life Cycle Data System – ILCD Handbook" (EeB.NMP.2012-5).

Compared to the currently available windows (state-of-the-art), the expected improvements from the funded projects on "Smart Window" were: (i) reduction of U-value down to 0.3 W/(m^2 K); (ii) weight reduction of at least 50%; (iii) cost reduction of at least 15%; (iv) improved energy efficiency in buildings by 20%; and (v) greenhouse gases reduction deriving from buildings in Europe.

Out of the five expected improvements, only one (greenhouse gases reduction) is discussed in the present paper. For sake of clarity we want just to mention that with respect to the first two objectives the weight reduction goal was reached by 100% at a U-value of 0.5 W/(m^2 K) and this is an important result since significant progress beyond state-of-the-art was required in numerous fields to fulfil these project goals. The total energy savings vary from 6% to 25% according to the building and climatic scenario. The details on the final performance of the window will be disseminated at the end of the project.

2.3. Short description of the project

HarWin (Harvesting solar energy with multifunctional glass-polymer windows) project (www.harwin-fp7.eu) is an inter-organisational R&D project that involves two Universities, six firms and two Research institutes and it runs from September 2012 until (August 2015). The specific objective of the Project was the development of multi-purpose windows (Fig. 1a) based on:

- Laminated glass containing new materials, not yet utilized for glazing;
- Glass-polymer composite interlayers, that are mechanically reinforced materials which enable weight reduction, high visible light transmission, thermal and sound barrier enhanced properties (Fig. 1b);
- Latent heat storing elements such as phase changing materials (PCMs) integrated for additional energy efficiency;
- Polymer foam-glassfibre-reinforced framing (GFRP) for weight reduction (Fig. 1c).

3. Integration of life cycle aspects in the R&D project

3.1. Organization of the project

The detailed analysis of the structure of the Project is reported in this section with the aim of highlighting the formal integration of the environmental dimension into the project management. This is relevant since it has been found out (see Section 1) that one of the obstacles to a better consideration of environmental aspects in the PDP is such a lack of formal integration in the project management.

The HarWin Project has been structured in six Work Packages (WP), as listed below:

WP1: Material development for the interlayer of the specialized glass pane;
WP2: Glazing system (with added functionality for solar energy harvesting) development;
WP3: Integration of components;
WP4: Light weight frame development;

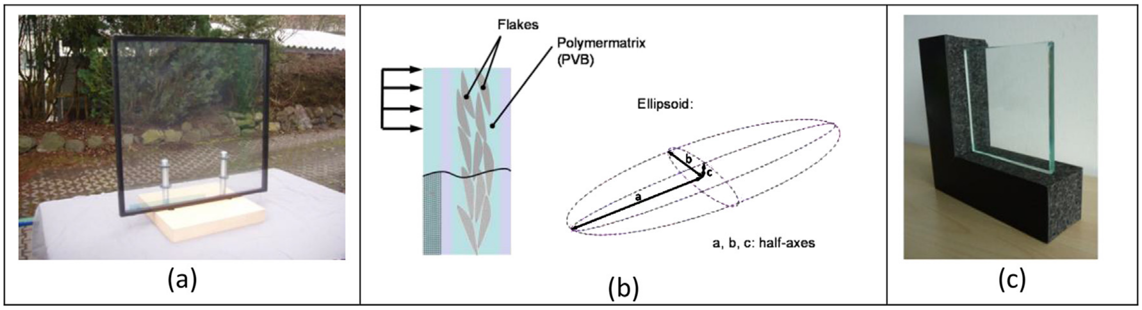


Fig. 1. Main components of the innovative smart window – a) First demonstrator, b) Design concept for the glazing system, c) Light weight frame.

WP5: Modelling of component performance and building integration;
WP6: LCA of windows integrated in buildings.

The four first WPs are technological and concentrate on specific features of the new window (i.e. glass material, glazing system, frame, integration of components) while WP5 and WP6 are more transversal.

The Project includes the specific WP6 on LCA of windows integrated in buildings. The Joint Research Centre (JRC) has been leading this WP, pursuing the following objectives:

Objective 1. To develop a Life Cycle based assessment method adapted to the project;
Objective 2. To support R&D decision making by analysing the life cycle environmental performance of the different technical solutions of window's components;
Objective 3. To develop and make publicly available LCI datasets for the materials and windows components analysed within the Project and hence to contribute to the dissemination of LCA knowledge and of the research outcome.

Although the analysis of environmental life cycle aspects was clearly the core of the WP6, it has been recognised the need of intense interactions with all the WPs. These explicit interactions were actually already established during the development of the project proposal. As an illustration, Table 1 shows the formal interactions between of WP3, WP4 and WP6[1], as they were proposed as deliverables and milestones in the initial proposal. The different colours of cells and text highlight the deliverables that the Environmental-team (E-team hereafter) led or contributed to and illustrate the flows of information among different WPs. Requirements, deliverables and milestones have been regularly discussed during the bi-annual consortium meetings (Table 1) among the partners in the Steering Committee. These regular meetings had the objective of communicating results internally allowing the most direct and effective interactions between the partners. More in general, the meetings turned out to bring the life cycle perspective among the project participants and hence to increase awareness of the potential of LCA.

Table 1 also shows that the above mentioned objective 1 was formally pursed through formal deliverables due at month 6 (WP6) and at month 18 (WP6) when a Life Cycle Environmental Assessment method specific for windows ("LCEA method" hereafter) including a method to assess the end-of-life of windows (the "recyclability method") has been clearly defined. The objective 2 was set up when a tailored "LCEA tool" (month 22 and WP6 in Table 1) has been defined and distributed to the D-team to allow it to include environmental aspects during the innovative window development. As result at month 24 (month 24 and WP4 in Table 1), a design decision based on environmental together with technical objectives has been taken. The "LCEA method", the "LCEA tool" and the design decision taken with the help of both of them are extensively further discuss in Section 3.2 and 4, respectively. Finally the objective 3 has been pursed starting from month 9 (month 9 and WP6 in Table 1), when a questionnaire has been distributed through the consortium members to gather the most significant primary data on materials and processes under partners' control. The integration of datasets into existing LCA database has been seen as a mean to disseminate the results of the project. In particular data were collected to publish the life cycle datasets through the Life Cycle Data Network (LCDN) (http://eplca.jrc.ec.europa.eu). The LCDN consists of a non-centralised database where several providers are facilitated in sharing LCI data and where the quality of the data is enhanced with specific quality requirements, hence contributing to better availability, interoperability and coherence of LCI data (Recchioni et al., 2015).

This organisational set-up has been already proposed during the preparation of the HarWin proposal, to ensure appropriate consideration of environmental aspects in the course of the project.

3.2. Tailored method and tool developed for the innovative window design process

This section describes the implementation of the environmental dimension within the HarWin Project through the development of a systematic method and a tailored tool to assess, at the R&D stage, the environmental burden associated to the life cycle of windows.

Within the first 6 months of the Project, the "LCEA Method" (Allacker et al., 2013) (Fig. 2), has been defined taking into account the Project objectives and context. The main features of this method are listed below:

- It is life cycle based (ISO 14040 and ISO 14044);
- It has a multi-criteria approach, the life cycle impact assessment includes 14 impact categories (as derived from the European "Product Environmental Footprint" (PEF) (EC-JRC-IES, 2012) and EN 15804:2012 (EN:15804, 2012));
- It is based on an iterative assessment process:
  - a *screening assessment* (based on generic data);
  - a *detailed assessment* (based on specific data and revised/refined building and window models);
  - a *final assessment* (bases on final specific data and final building and window models).

As shown in Fig. 2, the first iteration aimed at modelling the different building and window types and to define the base case scenarios. The evaluation of the environmental impact of base case

[1] The three other WPs of the HarWin project are here omitted for the sake of brevity.

Table 1
Objectives and related deadlines within the project plan for WP3, WP4 and WP6. Green cells = Deliverable/Milestones led by the E-team; yellow cells = Deliverable/Milestones led by the D-team to which the E-team contributed; text red-coloured = output from the E-team to the D-team; text grey-coloured = output from the D-team to the E-team. Last column on the right: bi-annual consortium meetings.

Months	WP3 Integration of components	WP4 Light weight frame development	WP6 LCA of windows integrated in buildings	Meetings
6			Definition of "LCEA method" and of Base-case windows	X
9			Datasheet for primary LCI data gathering	
12		Polymer foam core and GFRP shell frame: data submitted for LCI dataset		X
18	1st demonstrator: data submitted for the refinement of LCI dataset		Definition of the "recyclability analysis method" - Benchmark scenarios: Base case windows - Ranking of most influencing parameters	
22			Definition of "LCEA tool"	
24	2nd demonstrator: data submitted for the refinement of LCI dataset	Integration of LCA results in a decision to be taken on the frame design		X
30				X
36		LCA of the added values requirements for the innovative smart windows		X

windows as representative of the average product available in the market was useful to create a benchmark to which the design options (e.g. concerning the materials of the frame, the glazing system, the manufacturing processes, etc.) of the novel window have been compared to in the next iterations. Initially, the datasets to be used to analyse the components of the innovative window have been based on generic data. Successively the datasets have been continuously updated and refined with the new data available at the next stage of the development process. A spreadsheet and a questionnaire for collecting data were created by the E-team and then validated by project partners. Moreover direct data were collected by the E-team directly visiting laboratories of the novel materials under development (e.g. of the specialized interlayer, of the glass flakes production) and of the manufacturing plants for glass coating and frame production. In addition, experts from the industry (e.g. the association EuroWindoor (http://www.eurowindoor.org)) actively contributed to the characterisation of the base case scenarios. The validation of the spreadsheet for data gathering was the earliest opportunity to find the right compromise between the desirable accuracy of data, as requested in particular by the LCDN (http://eplca.jrc.ec.europa.eu; Recchioni et al., 2015), and the real possibility by technological partners to supply the data required. The experience gained with a first complex and demanding questionnaire brought the E-team to define a simplified datasheet. At a further step, visual flow diagrams have been added to guide the users. According to members of the D-team, these diagrams were helpful to link input data for the LCA to each step of the design of the window.

Finally, Fig. 2 shows the connection of time and efforts (horizontal axis) with quality and robustness of LCI data and LCA results (vertical axis) but also with two important issues typically addressed by the environmentally conscious design, which are:

- Early integration of the environmental aspects into product design;
- Internal communication between the actors of the design process.

During the project it was experienced that the quality of LCI data and LCA results increased over the time in terms of accuracy, precision and completeness. This was linked to the progressively ease in the exchange of relevant data and information between the different expertise within the consortium. On the other hand it was observed that, at any subsequent step, the possibility of LCA results to influence the product development decreased. For this reason, as recommended by (ISO/TR 14062, 2002), an early integration of environmental aspects into product design plays an important role for the product development.

With the aim of applying what have been set with the "LCEA method", the "LCEA tool" has been developed. It is a software tool that allowed the D-team to almost autonomously assess and compare the environmental impacts of various innovative window components during their design. This ability of the D-team to handle the "LCEA tool" has been gained thanks to meetings, workshops and presentations organized during the initial stages of the project. All these dissemination activities brought a diffuse life cycle culture among the members of the project consortium. The availability of the "LCEA tool" was crucial to foster the R&D decisions towards the improvement of their functionality as well as their environmental performances. The main characteristics of

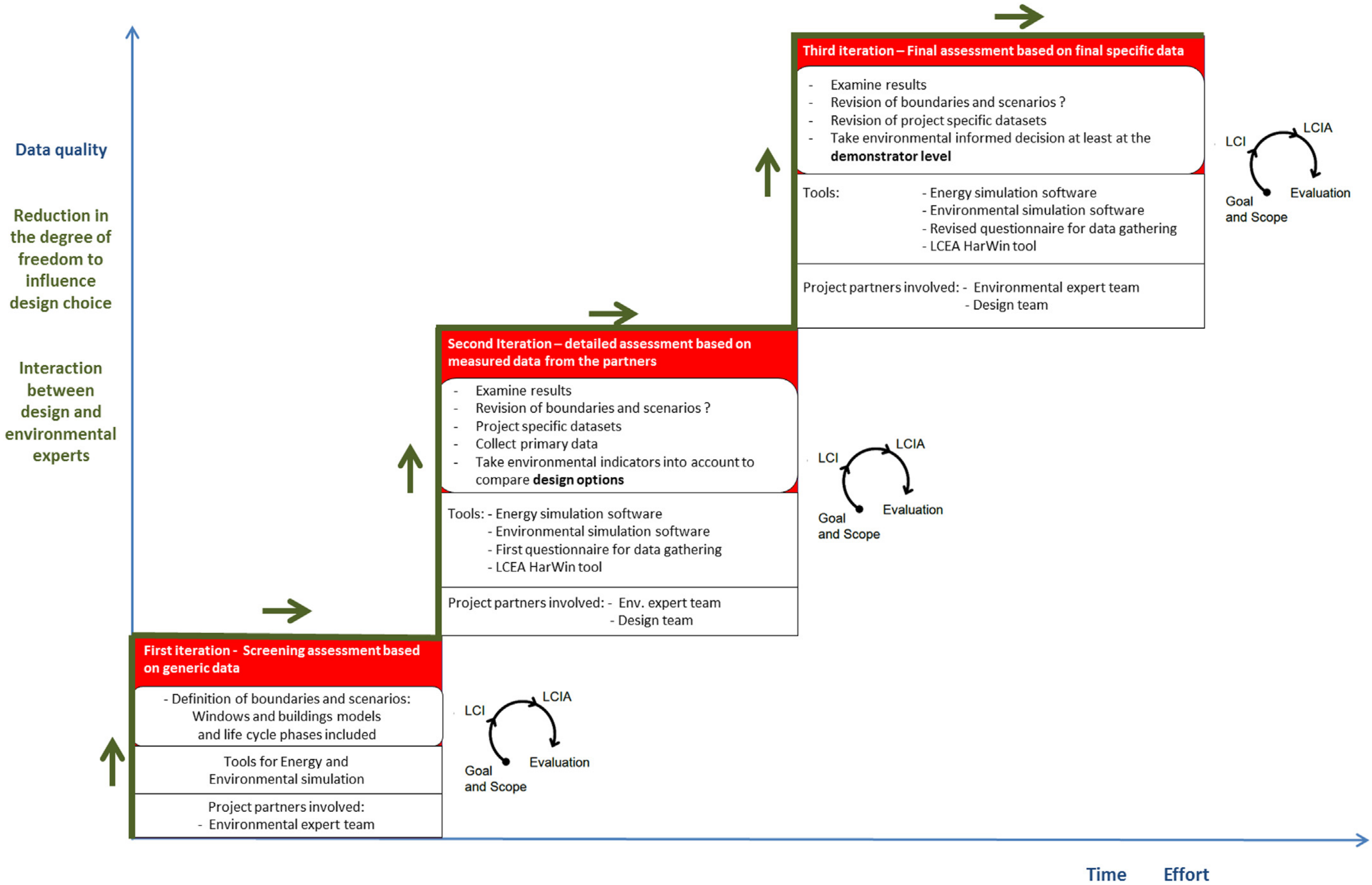


Fig. 2. Flow diagram of the "LCEA method" applied in the Project (adapted from EC-JRC-IES, 2010). Lines, arrows, text in green highlight the environmentally conscious design aspects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the tool that allowed its use by non-LCA experts were the following:

✓ The tool is presented in the format of an Microsoft (MS) Excel tool;
✓ The datasheet is made of worksheets related to the Work Packages (WPs);

The tool has been thought to help with the identification of the most influencing parameters under the environmental point of view. For this reason there have been defined:

✓ Appropriate tables to digit the input of specific design parameters;
✓ Appropriate tables and graphs to show the results: the results are expressed through a predefined set of environmental impact indicators, combining indicators recommended by the PEF (EC-JRC-IES, 2012) and by EN:15804 (2012).

In the "LCEA tool", each worksheet is dedicated to a specific aspect of the design (i.e. frame, glazing system, whole window, distribution phase and use phase at building level). Each worksheet is made of three main sections. As it is shown in Fig. 3, the first section is set for data input (Fig. 3a); the second section (Fig. 3b) is automatically filled with previous information and it lists the LCI data (inputs/outputs flows of materials and energy); finally the third section (Fig. 3c) displays the outputs (environmental impact indicators) in terms of histograms and tables, based on LCIA characterization factors (EC-JRC, 2011) for each data input that are embodied in the software tool. The results are presented in each worksheet in a simplified and user-friendly way in order to facilitate the identification and ranking of the most influencing material/components/processes (e.g. glass fibres and injection moulding for the frame worksheet, as presented in Fig. 3c) and ultimately to guide the material selection during the design phase.

Moreover, an additional worksheet presents appropriate tables and graphs to visualize the environmental impacts of innovative window options in comparison to the benchmark scenario made of a panel of average windows (base case) available in the market. In particular an Ashby diagram was tailored to the need of the Project. This type of diagram allows to compare different objective functions at the same time in the same Cartesian plane (as proposed e.g. in (Ashby, 2005)) as explicitly required by the "Smart window" call. Fig. 4 shows the two selected objective functions: the environmental impacts (Climate Change[2]) and the mass of the window. Both the objectives are required to be minimized for the innovative windows designed in the Project (see Section 2.2). In the same figure the red dots represents the specific design option evaluated at a certain step of the design process. For example, red dots in Fig. 4 illustrate two examples of innovative windows designed at different stages of the project (Demonstrator 1 and Demonstrator 2). This kind of presentation proved to be particularly useful for the Project manager and informative for the Project partners during the review of the R&D project that were held during the bi-annual

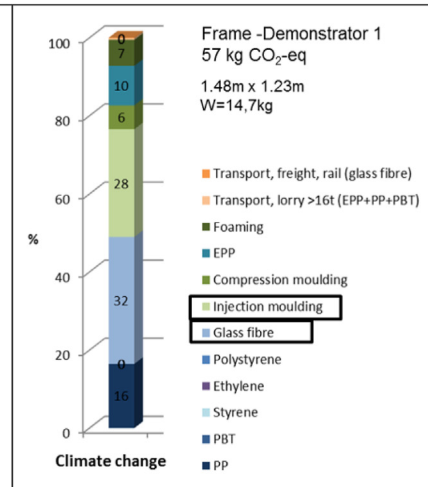
[2] The tool displays separate Ashby diagrams for all the considered impact categories.

Step 3		
Decide the volume fraction of glass fibre		
35	%	
Step 4		
Decide the weight fraction of compatibilizer. Note: more optimal		
0	%	
Step 5		
Decide the styrene and ethylene/butylen polystyrene content		
35	%	Styrene
35	%	Ethylene
30	%	Polystyrene
Step 6		
Decide the ratio between PP and PBT		
99.9	%	PP
0.1	%	PBT
Step 7		
Decide the distance for glass fibre transportation		
300		
Step 8		
Decide the distance for EPP+PP+PBT transportation		
100	km	EPP
300	km	PP
300	km	PBT

(a) Data input.
The black cells are filled manually or via drop down list.

LCI Frame		
PP	kg	4.73
glass fibre	kg	7.00
Injection moulding	kWh/kg	1.48
Compression moulding	kWh/kg	0.995
EPP	kg	2.91
Foaming	kWh/kg	0.788
Transport, lorry >16t (EPP+PP+PBT)	tkm	1.71
Transport, freight, rail (glass fibre)	tkm	2.10
Weight of the frame for HarWin window [kg]		14.65

(b) LCI.
When data input are digit the cells with the amount are automatically filled.



(c) LCA Output.
Graphs and tables are selected to show the results.

Fig. 3. Flow chart of "LCEA tool". Each worksheet is structured according to three main sections a) b) c).

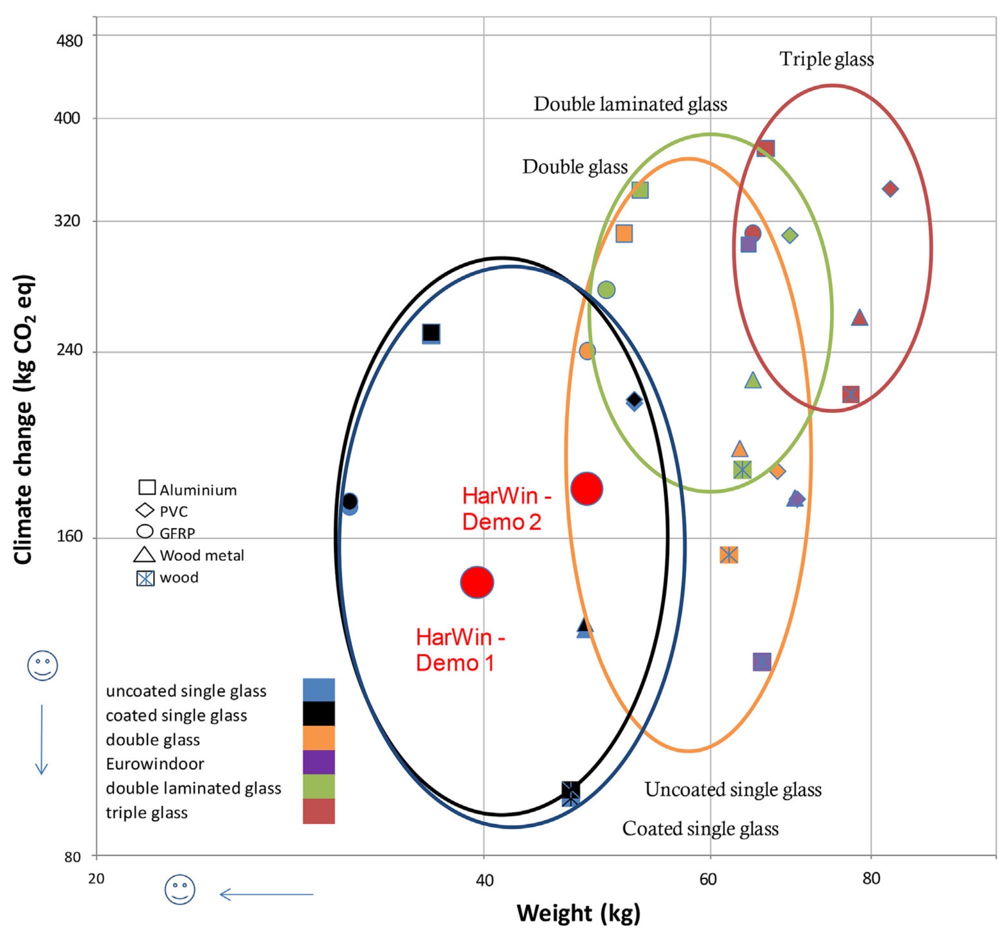


Fig. 4. Ashby-type diagram with two parameters to be minimized by the analysed design options (Demo 1 and Demo 2): the environmental impacts (Climate Change) and the mass of the window.

meetings, and especially when demonstrator 1 and demonstrator 2 were issued.

4. Example of an environmentally conscious design decision taken in the course of the project

This paragraph describes the process which led to a design solution for the frame component which satisfies the technical needs and in addition minimizes the environmental impact. The decision making process was led by the University of Bayreuth, partner of the project and member of the D-team and in particular of the "frame design team" (hereafter FD-team). Fig. 5 illustrates the main steps of the environmentally conscious design process developed for the design of the frame of the innovative window:

1st step: Identification of an initial design option;
2nd step: Finite element simulations;
3rd step: Manufacturability analysis;
4th step: Environmental analysis;
5th step: Verification of the objectives.

The final solution was identified after the technical and environmental analyses and after checking the matching to the aims set before starting the process and based on the Project main objectives.

Fig. 5 also shows that, during the development of the project, as it is usually verified in any development project, the level of knowledge about performances of the frame increases while the number of possible design alternatives decreases.

Before starting the design process relevant design objectives have been identified. In particular the general objectives of the project have been evaluated (see Section 2.2) and integrated to the specific requirements of the frame components. Therefore the following five objectives have been defined: *Minimize weight, increase stiffness, fulfil environmental requirements, reduce stress, and verify the manufacturability*. The objectives have been translated in five target functions to be verified simultaneously. Than the availability of software tools, measurement instruments and specific expertise have been checked. The two objectives *Minimize weight* and *fulfil environmental requirements* could benefit of the availability of the "LCEA tool" and rely on the support of the E-team of the consortium. To *verify the manufacturability*, experts in the production process of the frame component could be consulted with the project consortium. Moreover the FD-team had internally the necessary expertise and tools to carry out finite element simulations and therefore to deal with the *increase of the stiffness* and *the reduction of the stress*.

A detailed description of the environmentally conscious design process follows:

1st step: Identification of the initial design option. It is a glass fibre reinforced polymer (GFRP) frame with a fraction PP-GF60 (GF 60% in weight) and the uniform thickness of 2.7 mm.

2nd step: Finite element simulations. Since the FD-team could manage to handle the mechanical issues internally, finite element simulations were carried out as first step. In order to model the window structures as realistic as possible, the FD-team applied an orthotropic material model for the fibre reinforced frame. The calculated stiffness and stress values belong to a realistic wind load case which occurs at typical window applications. In addition, the coupling of the frame and the glass panes was captured by appropriate finite element contact modelling. From these simulations came out the need of reducing stress at the edges to guarantee the mechanical stability and the need of increasing thickness to raise the overall stiffness. These evidences brought the FD-team to re-design the initial design option. That process brought to a set of five alternative design options, each one characterized respectively by: 1) the use of rounded edges; 2) the use of additional glue in the edges; 3) the use of metal reinforcement in the edges; 4) the increase of the whole frame thickness; 5) the increase of the thickness of the frame only along the edges. The first three options were more focused on the objective of fulfilling stress requirements, the fourth on the stiffness requirements and last one have been thought as a compromise to increase stiffness and reduce the stress where it was higher.

3rd step: Manufacturability analysis. All the five design options were brought to the attention of the expert of the frame production team. The first three options were judged as inadequate because they were incompatible with the manufacturing process. Only two options went beyond this step verification.

4th step: Environmental analysis. The two remaining design options have been evaluated more in details by FD-team through the lens of the environmental performance. The improved solutions should have an overall increased environmental performance that means at least a better performance during one phase of the

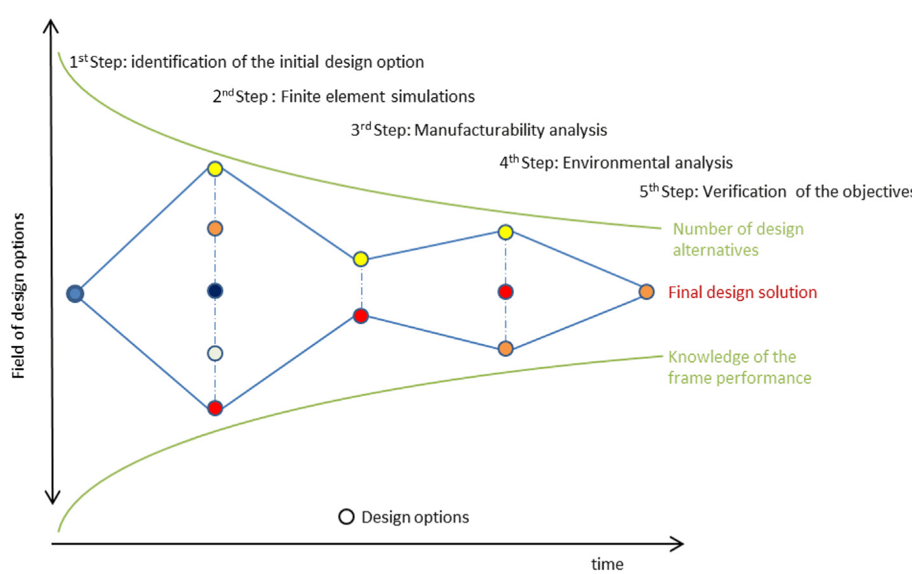


Fig. 5. Environmentally conscious design process (adapted from (Kortman et al., 1995) to the HarWin context). It illustrates the number of solutions in the field of the design option.

life cycle without compromise the others. At first the environmental impact of the energy and material flows involved in the production phase of the two design options has been compared through the "LCEA tool". It resulted that both the two solutions increased the amount of material processed and therefore both the mass and the environmental impact of the component with regard to the initial design option (uniform thickness of 2.7 mm).

Since the "LCEA tool" was thought in a way that many relevant design parameters can be varied (e.g. overall thickness of the frame, the fibre content, the global dimensions as height and width) the FD-team identified the opportunity to change independently the thickness in the edges and in the other parts of the frame. In order to capture frame sections with different thicknesses the "LCEA tool" has been modified by the E-team. This modification made the tool more adapted to the R&D context and allowed to investigate more design options. Moreover this step sensibly increased the trust in the results of the tool within the DF-team since they could work with the E-team to make it more adapted to the specific design requirements. Finally a third design option (as a beneficial compromise between the two analysed alternatives) came out from the environmental analysis: a tailored frame with increased thickness in the edges but reduced thickness in all the other parts ($d_E = 3$ mm and $d_F = 2.4$ mm in Fig. 6).

The FD-team of the Project recognized that the "LCEA tool" was in this case a source of inspiration, contrary to the scepticism of some authors found in literature (e.g. Millet et al., 2007) according to which the use of an LCA tool could represent an obstacle to the creative process. The analysis of this R&D sequence proved that the assessment of the product from a life cycle perspective brought the designers to an innovative structure of the window frame and therefore to experience an unexpected creativity during the design process.

5th step: Verification of the objectives. On the basis of the results obtained by the "LCEA tool", the tailored frame design option (TDF) has proven to be the best option in terms of environmental impact due to the production phase of the frame life. Nevertheless, to be identified as the most promising design solution, it had to fulfil all the other objective functions. The last step consisted of the verification of all the remaining requirements, in particular:

- Objective function – *minimize the weight*: reduction of the weight with regard to the not tailored frame has been verified (reduction equal to 8%);
- Objective functions – *increase stiffness* and *reduce stress*: the tailored frame has proved to satisfy all the mechanical requirements once analysed through the finite element simulations (edge stress from 7.6 N/mm^2 to 5.7 N/mm^2, reduction equal to 25%)
- Objective function – *fulfil environmental requirements:* the tailored frame has proved to satisfy *environmental requirements* during the production phase (Fig. 7) also in terms of energy efficiency of the manufacturing process. Compared to the initial design option ("uniform 2.7 mm" Fig. 7) the reduction in the environmental impact varies from 4 to 5% (according to the different impact categories). Fig. 7 also shows when the TDF is compared to the design "uniform 3 mm", in this case the environmental impact is reduced by about 11–14%. A suitable manufacturing process (still evaluated only at the laboratory scale) is a two-step process, which first step is "consolidation" and second step is "thermoforming". To the first step is related the consumption for a double band press (heating and pressing), whereas the consumption of an oven and a press is associated to the second step (the frame shell material has to be re-heated in the oven). The environmental impact is expected to be lower for the tailored frame than for the uniform frame, since the first one has a lower amount of material with higher heat capacity (e.g. glass or basalt fibres) and this is beneficial during the heating process.
  The tailored frame is expected also to satisfy *environmental requirements* during the other phases of frame life i.e. use phase and end-of-life phase. Regarding thermal properties of the frame, the change of the thickness of the shell in the corner can be neglected due to the difference in thermal resistance and total thickness of the BFRP material used for the shell and the foam used for filling the frame. Almost all the thermal resistance of the innovative frame is due to the foam layer. This means that the tailored frame design has a very low impact on the U-value. Finally, in the end of-life of the frame the tailored structure do not represent an obstacle to the recyclability of the frame: the only difference between the uniform and the tailored frame is that additional layers have to be inserted in the edge region but there is no adhesive or other additional junction technology required;
- Objective function – *verify the manufacturability*: the differences between uniform and tailored frame in the manufacturing process can be neglected, because the only difference is that additional layers have to be inserted in the edge region whereas no additional non-reversible junction technology is required.

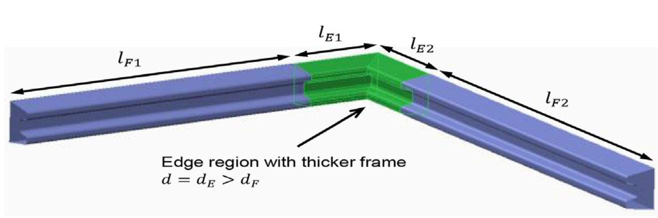


Fig. 6. Innovative design option: thicker frame in the edge region (tailored), but reduced thickness in all the other parts of the frame.

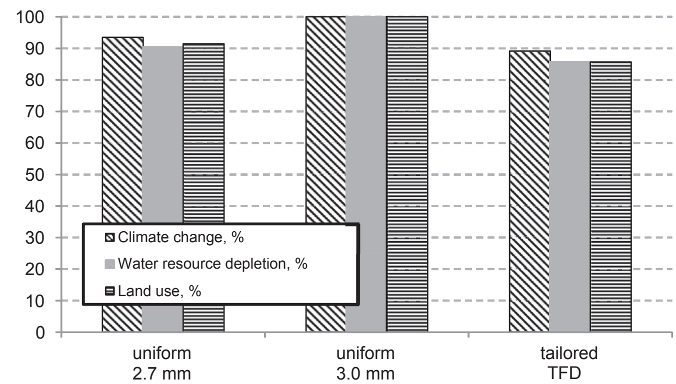


Fig. 7. Three frame design options have been compared using the "LCEA tool". Two design options with uniform thickness and the third obtained by changing the thickness in the edge region independently from the other part of the frame (tailored). The LCA results are expressed according three selected impact categories.

To conclude, the tailored frame design option has been identified as the most promising design solution since it fulfilled all the objective functions.

5. Discussion: how to better integrate environmental considerations in R&D inter-organizational projects

The management set-up and operational methods and tools deployed in the HarWin project have been analysed in the previous sections to better understand how environmental considerations have been considered in this specific project. It was in particular showed how LCA was implemented as an efficient support for guiding the environmentally-conscious development of innovative products. This section aims at analysing further the knowledge gained during Project development, to discuss it taking into account the literature and to formulate recommendations for future projects and calls.

Table 2 summarizes the main limitations (in the first column) found in literature about the integration of LCA with R&D Projects in companies and inter-organizational consortia, as discussed in Section 1, and how these obstacles have been overcome in HarWin (in the second column), as discussed in Section 2, 3 and 4. Based on the latter, Table 2 also tentatively presents some more general recommendations concerning a better integration of environmental issues in R&D inter-organizational projects (in the third column).

In particular, it was found out that some of the difficulties encountered by companies in the integration of LCA with R&D Projects are more easily managed by inter-organizational consortia. This is mainly due to the constraints for the entry of innovative products into the market such as short time for product development and high costs of the research/expertise/tools. Other obstacles were managed by inter-organizational consortia thanks to the systematic addressing of the environmental issues along the whole project development and the set of specific WPs.

In summary it came out that to effectively deal with environmental concerns, an R&D Project should benefit of an adequate budget, enough time to develop specific methods and tools, a team of environmental experts to ensure the integration of the environmental issues in the product development and a management plan to support this incorporation. The approach for the integration of the environmental dimension in PDP is a topic already discussed in literature. For example, according to Dufrene et al. (2013) there are three options: the integration of new experts into the D-team (but design teams cannot continue to grow at the pace of the

Table 2
Limitations for integration of LCA in eco-innovation, lesson learnt from the Project and recommendations for other R&D inter-organizational projects.

Limitations	Innovations/solutions during HarWin Project	Recommendations for other R&D inter-organizational projects
Lack on integration of environmental dimension into the project management (Brones et al., 2014; Dufrene et al., 2013; Bovea and Perez-Belis, 2012; Lindahl, 2006)	The Project plan included one WP dedicated to LCA (WP6) and WPs on the main components development. Within each WP the relationship of the LCA activities with the design stages was clearly defined.	As a support to environmentally conscious design, a tool like LCA should be formally integrated in the initial project plan (e.g. in the "Description of work" that is the technical contract between the EU and the consortium); moreover, deliverables and milestones should explicitly capture LCA activities to support decision making in the project.
Cost issues (Baumann et al., 2002)	An adequate budget was set to carry out the environmental tasks: ≈500,000 out of ≈5,000,000 equal to ≈10% of the overall budget.	Inter-organizational R&D projects should allocate enough resources within the project for a team of experts full time committed into the environmental tasks.
Timing issues (Brones et al., 2014)	Environmental tasks were distributed along the 3 years of the project. Within the first six months the method for the integration of the environmental aspects in the PDP has been set.	Inter-organizational R&D projects should last enough to perform a comprehensive environmental analysis (3–4 years are recommended). Environmental aspects should be integrated early in PDP (after the first six months at latest).
Insufficient knowledge of the environmental issues by the product developers (Le Pochat et al., 2007; Dufrene et al., 2013; Millet et al., 2007)	The need of expertise in the LCA has been coupled by dedicating 36 Person/Month specifically to environmental tasks (E-team).	Inter-organizational R&D projects should involve a team of experts fully committed to LCA and environmental aspects that can ensure the integration of the new expertise by tailored tools and methods and can support design decisions.
Cultural complexity (Sandin et al., 2014)	During the Project, meetings and workshops have been periodically organised on technical and environmental topics. Over the time, the knowledge and confidence on the LCA method and tool have increased between the partners of the consortium and also the expectation of the D-team has been tuned to the LCA objectives.	Inter-organizational R&D projects should boost fast learning and cooperation between technical experts/ developers and the environmental experts.
Lack of follow-up on the choice of methods and tools (Lindahl, 2006; Millet et al., 2007)	At a specific moment in the Project plan the D-team was able to take formal decisions since its members have confidence in the LCA method and tools. In particular they became familiar with the use of the LCA tailored tool (developed by the E-team). Moreover they contributed to the refinement of the same tool in a way to make it able to fulfil the specific design requirements.	The LCA method and tools should be tailored and based on needs and suggestions of the D-team. This increases the confidence of the product designers on the LCA tools and their perception of the reliability of the results. Consequently, it makes easier to take decisions based on LCA outputs.
Perception of LCA as a stumbling block to creativity (Millet et al., 2007)	The D-team of the Project consortium stated that the analysis of the design options through the life cycle approach allowed them to develop an innovative solution. The unexpected outcome, generated through the tailored design tool, was a proof of unforeseen creativity they experienced during the design process.	Life cycle tools should be built and integrated in the design process in a way that the product developers can perceive them as a source of inspiration more than an obstacle to their creativity.
Uncertainty on how to prioritize environmental issues against other factors (Bovea and Perez-Belis, 2012; Millet et al., 2007; Ardente et al., 2003)	The objective of balance the environmental requirements against other traditional requirements (Technical/Quality/ Safety) was carried out through a multi-criteria approach. Target functions has been analysed through the lens of a panel of impact categories.	The objective of the environmentally conscious design process should be clearly defined since the beginning of the project. It should be made explicit through technical and environmental target functions to be possibly verified simultaneously.
Difficulties in collecting reliable and detailed data (Sandin et al., 2014; Dufrene et al., 2013; Lindahl, 2006)	Primary data from industrial partners have been collected and used together with quality assured secondary data from available databases (ELCD, Ecoinvent).	The need of environmental data related to the materials and processes from the industrial partners should be clearly and formally defined since the beginning of the project. Confidentiality issues can be overcome by formal agreement within the consortium. The call should explicitly require the publication of publicly available datasets.

integration of every new expertise), to ask a team member to assume multiple roles (but becoming a multi-expert he will reduce its level of expertise), or to support the integration of the new expertise by tools and methods to be used by the D-team.

The HarWin Project was a laboratory for this third approach, the two pools of experts maintained their specific roles and their autonomous point of view but at the same time was "forced" by the management plan to cooperate on the environmental issues and on a bi-directional education process.

A Stage-Gate system (Brones et al., 2014) gave the structure to the management plan since deliverable and milestone fixed the series of activities (stages) to be done, environmental assessment included, and the decisions (gates) to be taken before moving to the following steps. This structure allowed the D-team to maintain the specific role of taking design decision and the E-team to develop specific and tailored method and tool for allowing environmental informed choice. In particular the E-team dealt with technical aspect such as how to collect reliable LCI data, how to obtain reliable LCA results, how to prioritize environmental burdens in a multi-criteria approach. Moreover both the teams of experts dealt with specific issues to boost cooperation. In particular the E-team was engaged in how to make the LCA tool tailored to the need of the D-team, how to make the tool easily accessible by the D-team, how to bring into the design process inputs for innovation. The D-team, on the other hand, dealt with the collection of environmental data required by the D-team, the learning of the tool designed by the E-team, the need for the refinement of the tool when technical requirements occurred on of the materials and component under development. To conclude, it is worth remaking that cooperation and education played a key role to make the R&D project a successful example for the integration of environmental aspects in PDP.

6. Conclusions

The need to adopt a life cycle approach in the all types of technological development process is constantly increasing, in particular in the industry. In some recent publicly funded calls, LCA is proposed as a tool to support decisions: it was in particular required by the FP7 "Smart Windows" call published in 2011. This article presents the experience, the difficulties encountered by one consortium awarded in this call, when striving for the integration of Life Cycle approach into the development of innovative windows. It also reports the applicable strategies that were developed to overcome obstacles. R&D project dealing with innovative windows seems a relevant case study since this product group has been recently tackled by several scientific studies and policy initiatives in the area of materials innovation for the energy and environmental protection. Moreover, the quest to saving energy (e.g. better insulation performance of the envelope components, more efficient conditioning and lighting systems) and to integrating in buildings renewable energy technologies (building-integrated photovoltaic (BIPV), micro-scale wind turbine, geothermal heat pump (GHPs)), while avoiding the environmental drawbacks and eventually to reducing the overall emissions in the construction sector is stimulating both policy and academia activities toward the approach of the holistic environmental evaluation of building components (product level) into the performance of the building (system level).

The paper aims at providing methods, tools and recommendations on how to integrate this approach into the R&D design process carried out by inter-organizational consortia. As described in Section 3, tailored method and tool have been developed for the HarWin window design process. The "LCEA tool" is applicable for the R&D of other types of "Smart windows". The "LCEA method" should also be applicable to the R&D process of other products and in particular of other construction components and materials (both energy related products and renewable energy technologies integrated in buildings), since it allows the evaluation of the environmental performance of each component (product level) in the context of the whole building performance (system level). More generally, the structure and main features of "LCEA tool" should represent a valid example whenever a design tool has to be developed for integrating environmental aspects in the decision making process of any innovative products.

The initial objective of taking design decisions based not only on technical but also on the environmental performances was reached while dealing with frame development as reported in Section 4. The Project organizational set-up is also discussed in this paper as an example for evaluating the integration of the environmental dimension into the project management. In particular the main features relevant for the positive outcome of the project were identified to provide guidance for a better integration of LCA in inter-organizational R&D projects. First of all it came out the importance of clearly define at the beginning of the project the objectives of integrating environment concerns in the design process (see Section 2.3). At the same time it was stated the need of interaction and cooperation, e.g. on the materials and processes data gathering to make quality assured LCI datasets. It was experienced that the exchange of relevant data and information between the different fields of expertise and different partners within the consortium increased life cycle data quality over the time in terms of accuracy, precision and completeness. In this regard we recommend that future call explicitly require the publication of publicly available datasets. This will bring to a virtuous circle since future LCA studies (carried out both by companies and inter-organizational consortia) can benefit of the availability of updated datasets.

Other relevant outcomes, more related to the project management, deserve to be highlighted since we experienced that successful management measures have a key role in the successful use of LCA as a tool for Eco-innovation in R&D projects. First of all the project plan should include a WP dedicated to the environmental aspects and WPs dedicated to the design of the components where LCA is formally integrated. Then the project should benefit of enough time and economic and human resources (a team of experts full time committed in LCA) to perform a comprehensive environmental analysis. Moreover deliverables and milestones should capture LCA activities (e.g. LCI data gathering, definition of a tailored LCA method, definition of a tailored LCA tool to support decision making, LCI data refinement according to the project advancement as shown in Fig. 2). In particular the cooperation among the D-team and the E-team should be stated through deliverables/milestones to formalise relevant technical and environmental data exchange that occurs at each step of the product development (e.g. Design option 1, Design option 2, Demonstrator 1, Demonstrator 2, etc.).

All the management measures should guarantee a smooth integration of life cycle aspects in the design process and make easier to take decision based on LCA results with the involvement of the non E-experts. It was also experienced that an early integration of environmental aspects into product design plays an important role to influence the product development.

To make more effective the integration of LCA in inter-organizational R&D projects still remain some aspect that need to be improved. In particular it should be further analysed the effectiveness of collaboration tools to support co-analysis and decision (in this kind of R&D project, LCA expert are usually not based at the same place as other technical experts). Finally, it would be rewarding to further explore ways to quickly train technical experts on environmental and LCA aspects, so that the degree of freedom for the design of the first months is advantageously used.

This paper contains a lot of lessons learnt that should be valuable at various levels of R&D research project, including micro-level (i.e. R&D analysis and decisions carried out by experts), meso-level (i.e. management of the proposal and of the project) and even higher level (i.e. management of R&D calls and programs). It is hence hoped that reporting difficulties, successful strategies and lessons learnt during the HarWin project will be a source of inspiration for actors of publicly-funded eco-innovations, including partners, managers and initiators of research projects and calls.

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